

Rapid-Repeat SAR Imaging of the Ocean Surface: Can We Get Daily Observations?

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Introduction

Imaging of the ocean surface with a synthetic aperture radar (SAR) provides unprecedented detailed views of the ocean's short wave field as it responds to interactions with the atmosphere, longer waves, and currents. Useful and often intriguing spaceborne ocean radar imagery have been obtained for over three decades, starting with Seasat in 1978, followed by the Shuttle Imaging Radar (SIR) flights in 1984 and 1994, and through this decade with Russia's ALMAZ, Japan's JERS-1 mission and the continuing European Space Agency's ERS missions and Canadian Space Agency's RADARSAT. Key results on coastal processes (mesoscale circulation, surface and internal waves, slicks, and bathymetry) and sea ice using SAR have been widely published (e.g. various special issues in *Journal of Geophysical Research Oceans*: 88(C3), 1983; 99(C12), 1988; 98(C11), 1994; 103(C4), 1998; 103(7), 1998. Now, there is a growing interest in examining the atmospheric processes detectable on the ocean surface (see related papers within these proceedings), particularly mesoscale wind fields and boundary layer features. Acquisition of ocean imagery will continue into the next decade with the launches of at least 4 satellites carrying SARs: ESA's ENVISAT in 2000, Canada's RADARSAT II in 2001, Japan's ALOS in 2002, and NASA's LightSAR in 2002.

However, many of the ocean processes and particularly the air-sea interactions of interest for radar imaging have temporal and spatial scales that are largely under sampled by all of these SAR missions. This means that the utility of SAR for ocean studies has not yet been fully optimized. Our study is an attempt towards answering the following question: can a SAR mission be designed to provide observations of the ocean surface that more nearly match the spatial scales and temporal dynamics of the ocean surface and air-sea interactions, as needed for both science and operational requirements? We consider scenarios where either one or two SAR antennas are carried on a satellite platform.

Viewing the Ocean Surface

As illustrated in Figure 1, the time scales of ocean physical processes extend from minutes to years, with length scales from meters to 1000 km. Imagery from SAR provides key data for ocean swell, internal waves, mesoscale circulation including fronts and eddies, and a wide range of atmospheric processes. The latter includes measuring wind speed and direction, detecting atmospheric roll vortices and turbulence, plus identifying the extent and structure of storms and rain cells. Even the processes with relatively longer time scales such as fronts, eddies, and gyre circulation may fluctuate over a period of a few days or even less. In terms of operational

interests, ship monitoring (both fishing and traffic), detection of natural and anthropogenic slicks, identification of icebergs and sea ice navigation are perhaps best done with SAR imagery.

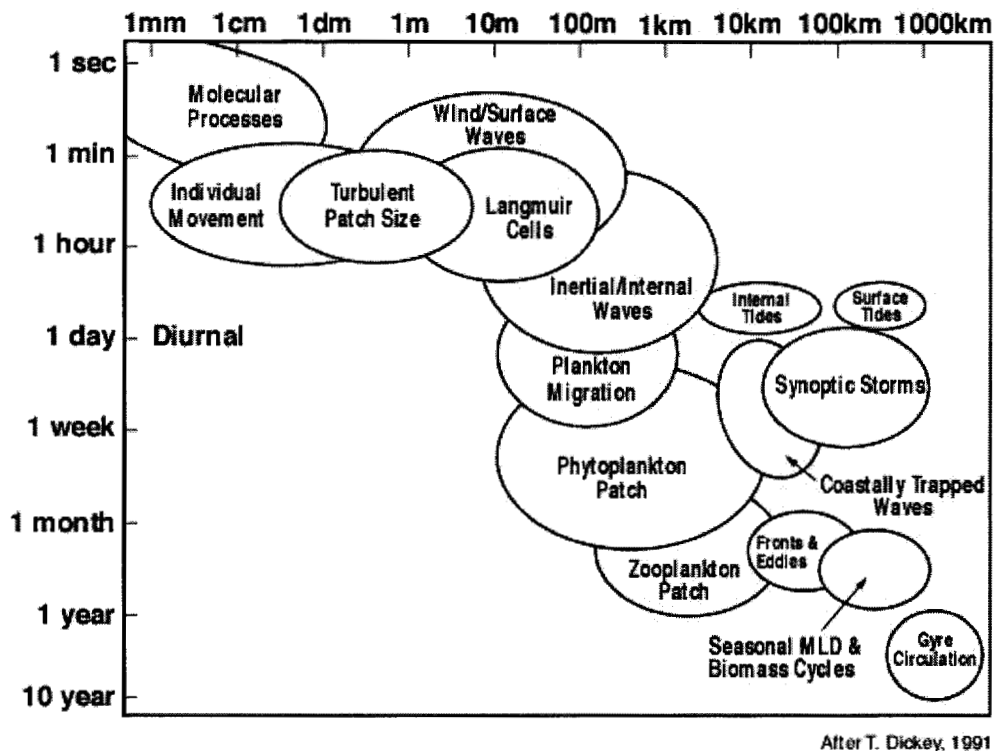


Figure 1. Time and space scales of key physical and biological processes in the ocean.

How is the ocean sampled from satellites? In general terms (and not including altimetry which is dedicated to 'gyre circulation'), the primary ocean sensors enable routine monitoring of nearly the entire global oceans every 12 hours-2 days. These include sensors for sea surface temperature and ocean color which have around 3000 km swath widths with 1 km resolution and provide twice-daily global coverage. Scatterometers for measuring winds have varying swath widths between 500-1800 km with resolutions between 25-50 km. Passive microwave imagers have viewing parameters similar to those of scatterometers.

As for SARs, Seasat, ERS-1/ERS-2, and JERS-1 have about 100 km wide swaths set at a fixed center incidence angle, resolutions on the order of 30 m, and orbital repeat periods generally greater than 3 weeks. The limited 3-day repeat periods of Seasat and ERS-1 were extremely useful for time series studies but resulted in large inter-orbit coverage gaps. For several months, ERS-1 and ERS-2 were in adjacent 35-day repeat periods separated by 1 day which also proved quite valuable for ocean studies. Both flights of SIR-C/X-SAR in 1994 had slowly precessing orbits that enabled daily and to a limited extent twice-daily observations using the ability to alter viewing

angles and direct the antenna (and shuttle) to view on both sides of the flight path. But each flight lasted about 10 days. Finally, RADARSAT provides a ScanSAR mode with between 300-500 km swath widths that enables imaging poleward of 50° latitude every 2-3 days as a result of orbit convergence. Equatorward of 50° latitude, a location can be seen with ScanSAR every 3-5 days. RADARSAT II, Envisat, ALOS, and LightSAR will have similar wide swath modes available, with RADARSAT II and LightSAR providing imaging on one or the other (not both at the same time!) sides of the flight path. All these missions have orbit repeat periods between 10-44 days. Even with approximately 3-day sub-cycles, routine ocean sampling will be problematic at these long duration repeat periods. Coordinating acquisitions to provide routine observations of any given region between sensors with different swath widths, orbital periods, and customer needs will be challenging to say the least.

How do we improve the sampling of the ocean surface with a SAR? To first order, the swath width can be increased. For a single spacecraft, this can be done by either increasing the swath width with one antenna or doubling the coverage with two antennas, each looking simultaneously on opposite sides of the subsatellite track. However, there are several inherent SAR-ocean sensing difficulties to be considered that result in conflicting design options.

Ocean backscatter has increasing sensitivity with increasing frequency, particularly in the relation of backscatter to wind speed (Unal et al., 1991). In general, C-band is preferred over L-band for most SAR ocean applications. In terms of power, lower frequency SARs have lower power requirements. For a given signal to noise ratio, for example, L-band is easier to accommodate on a satellite than C- or X-bands. Next, ocean backscatter falls off rapidly with increasing viewing angle as compared to other surfaces. This results in a comparatively narrow range of viable SAR viewing angles over which the ocean produces backscatter sufficiently above a reasonable noise floor to be detected as signal. Thus, simply increasing the swath width by viewing at higher angles is not feasible for ocean sensing, unless the orbital altitude is raised. However, on the positive side viewing at angles beyond this narrow range improves the detection of ships and icebergs because the ocean clutter becomes significantly lower than the target returns. The transmitted power required is sensitive to altitude, so raising the orbit would further increase the power requirement. Another consideration for ocean sensing is resolution. A standard trade-off in SAR design is between swath width and resolution, where increased swath width is often achieved with a concurrent reduction in resolution and vice versa. This is even more amplified when multiple polarizations are available. Users of SAR data have a natural proclivity for fine resolution and are often reluctant to move to reduced resolutions. Lastly going to a reduced resolution (say between 50-100 m) also raises the minimum detectable wavelength of surface

swell, making the data less useful for ocean wave studies.

Science Requirements for Rapid Repeat Ocean Mapper

We have put together the following science and operational requirements to help guide the design study, based on discussions with several colleagues and comments during the symposium (Table 1). For frequency, C-band generally provides better overall detection of ocean features and air-sea interactions than L-band, while X-band has higher power requirements. Vertical polarization over the ocean provides more ocean return than horizontal polarization (Unal et al., 1991). The spatial resolution for science was assisted by an analysis by G. Young (see reference in these proceedings), which is based on examining the turbulent scale of air-sea interactions. The operational resolution was selected to be more conducive for ship detection. The preferred range of viewing angles is 19-45°, while angles higher than 45° may be useful for ship and iceberg detection. A noise equivalent sigma zero of -20 dB provides sufficient signal-to-noise ratio for returns at low wind speeds at the larger 'science' angles. For coverage, global access is required. For satellite repeat interval, it is highly desirable to view a point on the earth with consistent viewing geometry and at about the same time each day. For this, we have selected a sun-synchronous orbit.

Table 1. Science and Operational Requirements

| | | |
|----------------|---|--|
| Science: | Mesoscale Circulation Features -currents, fronts, eddies, internal waves | |
| | Mesoscale Air-Sea Interactions -wind fields, atmospheric boundary layer processes | |
| Operations: | Ship detection - fishing, traffic | |
| | Pollution detection - oil slicks | |
| | Iceberg detection - seasonal in Atlantic | |
| Configuration: | Frequency | C-band (5.3 GHz) |
| | Polarization | VV |
| | Resolution-m/ Looks | Science - 150 /10 or more |
| | | Operations - 50 / 4 or more |
| | Incidence angle range | Science - 19-45° |
| | | Operations - 19-58° |
| | Noise equivalent sigma 0 | < -20 dB |
| | Coverage, Repeat orbit interval | Global access within <3 days , |
| | | consistent viewing geometry, sun-synchronous |

In addition to correlating better with the shorter term dynamic processes, wider and more frequent SAR coverage also provides a better complementary data set for use with the other ocean imaging sensors such as AVHRR and SeaWiFS. As a result, regional climatic-scale investigations that incorporate SAR will become possible. Of particular value will be studies of the coastal regions to examine the effects of significant climatic events such as El-Niño and resulting seasonal variations in weather patterns that alter the coastal environment both physically and biologically.

Study Options

Two study options we considered for a single spacecraft include using one or two antennas to achieve increased swath coverage. These configurations guided the mission and radar design. We describe each approach separately, discuss the resulting design configuration, and show examples of the approximate coverage from several orbital repeat intervals.

The selection of the orbital height and swath width is an iterative process. To aid in this, we use a simple graphical approach to approximate swath geometry at the equator and at 30° latitude for different repeat intervals over a fixed distance (longitude). The fixed distance is determined by the following approximation. Using a radius of 6378 km, the circumference of the Earth is about 40,074 km. We assume the nominal number of orbits per day to be 14 regardless of orbit height (more like 13 at 1300-1500 km) for graphical simplicity. At the equator, the separation between adjacent orbits is then about 2,860 km (25.7° of latitude). At 30° latitude, the separation is reduced to about 2300 km. A complete mapping with one viewing orientation with an 800 km swath requires 3.5 days at the equator or 3 days at 30° latitude. There is increasing overlap poleward of 30° which further reduces the sampling interval, but these are not included. We use the standard sun-synchronous orbit inclination of about 98°. From orbital tables, more specific altitude heights are then selected that corresponded to suitable repeat intervals.

One-Antenna Design.

To improve coverage with a single antenna while maintaining the constrained range of viewing angles for ocean sensing, the orbital height must be higher than the typical altitude of 800 km used by several spaceborne SARs (ERS, RADARSAT, Envisat). With viewing angles of 19-45°, a swath width of about 800 km is achievable at an orbital altitude of about 1400 km. From orbital tables, repeat intervals of 1-5 days are available between altitudes of 1319-1496 km. Figure 2 shows example coverage plots with an 800 km swath at 2-day and 3-day exact repeat intervals. The 3-day coverage provides about 85% complete coverage at the equator and complete coverage at 30° latitude. The 2-day repeat coverage is incomplete at 30° and the 4-day repeat (not plotted)

provides complete coverage at the equator with considerable overlap at 30 degrees. We selected the 3-day repeat option, which can be achieved at an altitude of 1368 km. The subsequent radar design is shown in Table 2, which includes the RADARSAT-1 ScanSAR Wide design for comparison (Luscombe et al., 1993).

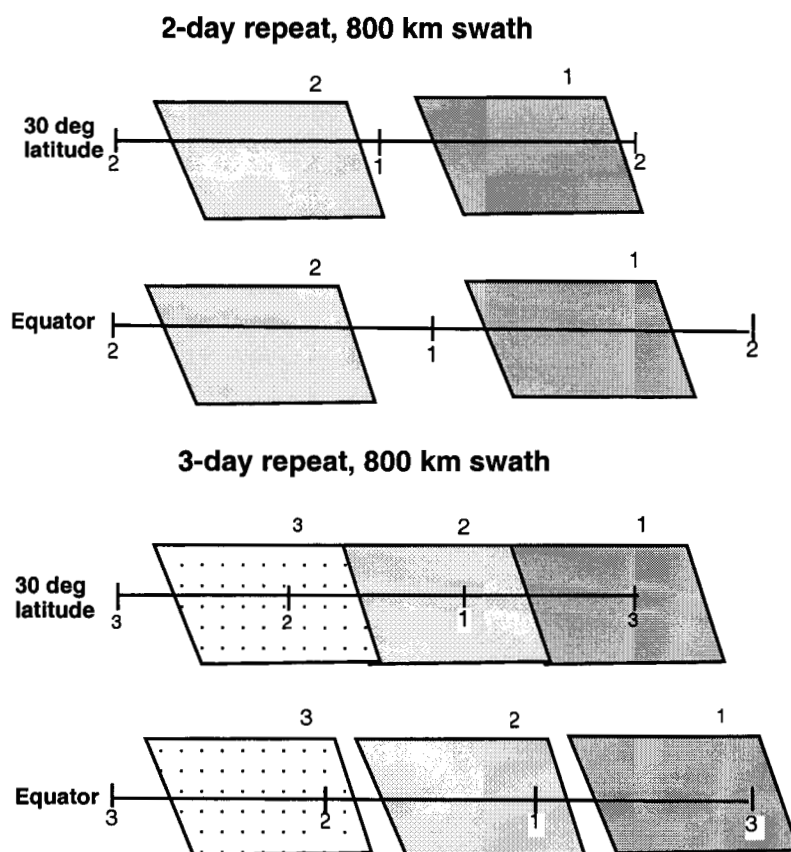


FIGURE 2. Approximate coverage with a 800-km swath (ascending orbits only, right looking) at the equator and 30° latitude, with a 2-day and 3-day exact repeat orbit. The axis length represents 2860 km (equator) and 2300 km (30° latitude). The orbit repeat day is indicated on the axis and corresponding swath. See text and Table 2 for further details.

The positive aspects of this design are that it makes use of one antenna and it matches the general requirements. We have assumed that the antenna is an active phased array. Also, the design is in consonance with RADARSAT-1 and thus is technologically within the state of the practice for instrument implementation. It should be noted that this is a feasible design for the mission design environment. Many design choices are possible to further optimize this design. For example, the azimuth ambiguity performance could be improved by lengthening the

Table 2. One-Antenna Design

| | <u>Ocean Mapper</u> | <u>RADARSAT-1</u> <u>ScanSAR Wide</u> |
|----------------------------|---------------------|--|
| Frequency/Polarization | C - VV | C - HH |
| Altitude-km | 1368 | 800 |
| Swath Width-km / Sub-Beams | 800 / 8 | 520 / 4 |
| Resolution-m / Looks | | |
| Science | 150 x 150 / 28 | 100 x 100 / 8 |
| Operations | 50 x 50 / 12 | |
| Antenna Dimension-m | 16.5 x 1 | 15 x 1.5 |
| Incidence Angle-deg | 23.9 - 52 | 20 - 49 |
| Data Rate-Mb/s | 60-97 | 105 |
| Bandwidth-MHz | 20 | 11, 17 |
| Noise Equiv. Sigma 0 - dB | < -21 | -20 |
| Azimuth Ambiguity - dB | < -15 (boresight) | -22 |
| Range Ambiguity - dB | < -21 | -18 |
| Peak Transmit Power -kW | 6 | 5.5 |

antenna. Other design choices must be made, such as the amount of beam overlap required which reduces the resolution in the overlap area. However, further design trade-offs are beyond the scope of this study.

The difficulties in this design are primarily attributable to the mission design requiring large area coverage (wide swath) and a short repeat cycle. To mitigate the incidence angle effects we chose a higher altitude. This altitude requires radiation-hardening to protect the instrument/system from exposure to higher radiation levels and more single event upsets (SEU) than what would be experienced at more benign altitudes around 800 km. The wide swath is achieved through the use of eight ScanSAR sub-swaths which makes processing and calibration more complex. While the orbit and swath provide complete coverage every 3 days (assuming the use of descending passes to fill in equatorial gaps), far better than any other current or near-term spaceborne SAR, the orbit and configuration don't really meet the central theme of near daily observations. The use of a second satellite in a duplicate orbit that is offset by 1-day would enable a second complete mapping with a 1-day and 2-day time separation.

An alternative concept to a low Earth orbiting (LEO) mission is to use a geosynchronous orbit which has an altitude of 35,768 km with an inclination greater than 0° . The well known geostationary (Clarke) orbit has an inclination of 0° . The inclined orbit provides a ground track that nutates relative to the surface of the Earth providing the required relative motion to form a synthetic aperture (Tomiyasu, 1983). The low velocity relative to earth provides a long beam dwell time compared to LEO missions. The geosynchronous orbit has a period of approximately 24 hr. Given a left looking SAR geometry, coverage over the east and west coast of North America can be achieved daily with two satellites, each at a 80° inclination with different ascending nodes (Figure 3). The geosynchronous orbit enables wide swath coverage (in this case approximately 540 km) over a narrow range of incidence angles with a single beam and a short revisit time. Because numerous communications satellites are in operation in equatorial orbits, the commercial launch and satellite industry has a large technology base from which to draw for a ocean mapping mission operating from geosynchronous orbit. However, orbital slots in geosynchronous planes may be limited and the possibility of collisions with satellites in the equatorial plane must be thoroughly analyzed. The disadvantages compared to LEO are that a large aperture and additional power is required to achieve the required radiometric performance.

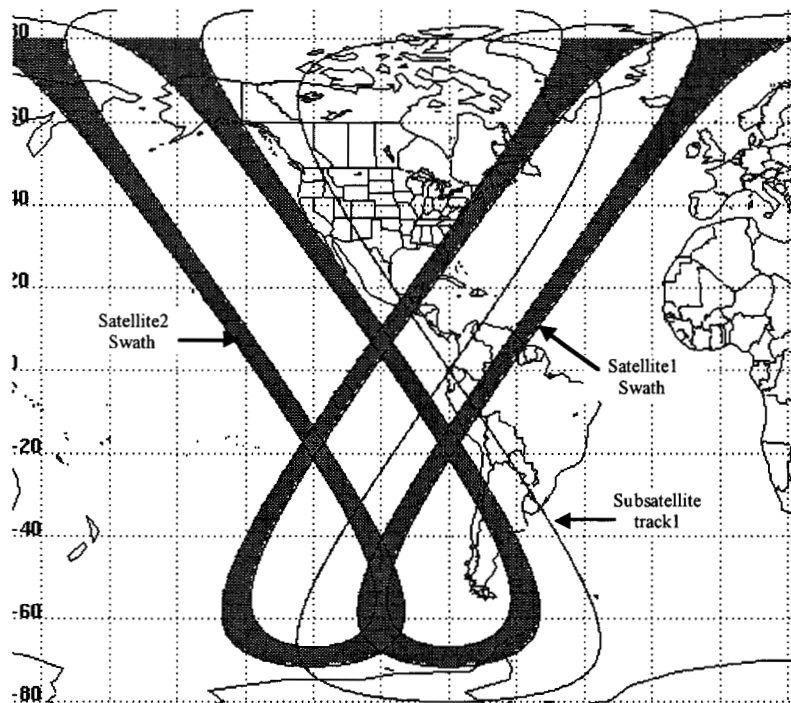


Figure 3. Coverage for two satellites each with a 560 km swath placed in geosynchronous orbit at 35,768 km altitude at inclinations of 65° over a 24 hr period. The ascending nodes are 240°E and 280°E (includes spacecraft nadir trace), respectively.

Two-Antenna Design

Next we examine a scenario where two antennas are carried on opposite sides of the same spacecraft. This would essentially mirror RADARSAT and Envisat in terms of a single antenna performance and coverage, but provide double coverage similar to the one-antenna design above. Also it would not require a higher altitude, but could operate at a more conventional altitude near 800 km. But what about the orbital design? In our graphical display, we examined two antennas with 400 and 500 km swaths, and repeat cycles of 3-6 days. Because of better coverage as well as sub-cycle coverage, we selected 500 km swaths for the study.

For two 500-km swath antennas (Figure 3), the 3-day exact repeat provides nearly complete coverage at 30° but the swaths have nearly complete overlap at the equator, with considerable gaps! A 5-day exact repeat provides complete coverage at the equator with considerable overlap with adjacent swaths. At 30° latitude, this repeat results in three sets of sliding 2-day and two sets of 3-day near-repeat sub-cycles. The 4-day and 6-day exact repeat orbits are less desirable because the sub-cycles are less useful. For the two-antenna design, we have selected the 5-day exact repeat orbit with two 500 km swaths. The orbital tables indicate an exact 5-day repeat occurs at 819 km altitude. The results of this design are shown in Table 3, again with the RADARSAT-1 ScanSAR Wide design for comparison purposes.

The positive aspects of this design are that the instrument and system mirrors satellites already in operations. While power must be sufficient to operate two antennas, this is less problematic than going to higher altitudes and may be solvable operationally rather than requiring key design development. Also, the 5-day exact repeat provides satisfactory coverage as well as improved sub-cycle sampling frequency. If a second satellite were implemented, it is likely that the orbits could be moved to a 3-day repeat orbit. By using a duplicate orbit with an offset equatorial nodal crossing, the second platform could map the equatorial gaps with 1-orbit offset in time as well as provide overlapping coverage at 30° latitude. There would then be complete coverage every 12-24 hours by taking into account the descending passes. A 3-day repeat orbit is available at 774 km altitude.

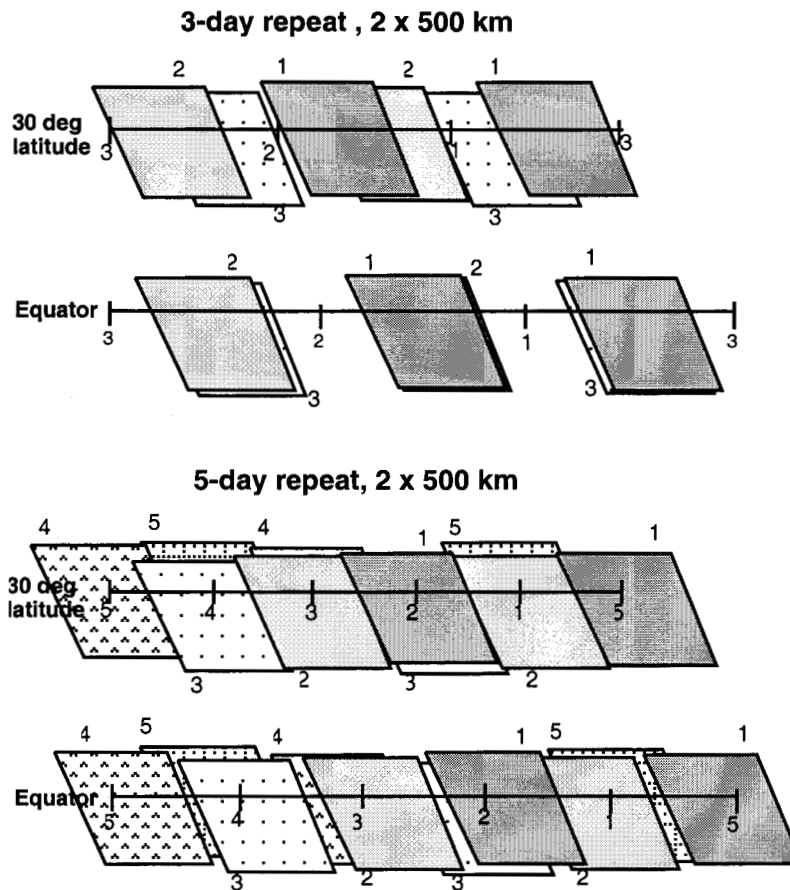


FIGURE 4. Approximate coverage with two 500-km swaths, one on each side of the spacecraft (ascending orbits only), at the equator and 30° latitude, with a 3-day and 5-day exact repeat orbit. The axis length represents 2860 km (equator) and 2300 km (30° latitude). The orbit repeat day is indicated on the axis and corresponding swaths. See text and Table 3 for further details.

In addition to transmitting with two antennas on a single platform, other negative aspects of the design are that it likely costs more than a single antenna design even with radiation-hardening and that it requires packaging of two antennas into a single launch vehicle. We note that Russia's ALMAZ-1 carried two antennas so such a concept has already been flown in space (albeit with heavy launch capabilities required too). For packaging into a Delta-2 scale launch vehicle, this may be solved by inflatable antennas which are being studied. Here the antennas are launched in a rolled-up configuration and then deployed as a thin-membrane stretched across a lightweight inflatable structure. The mass density of these antennas are a factor of three lower than conventional honeycomb designs, thus the launch constraint becomes the shroud volume and not necessarily the vehicle lift capacity. A key unknown for inflatable antennas, which would require on-orbit testing to verify, is the survivability of the membranes and structure in a space environment.

Table 3. Two-Antenna Design

| | <u>Ocean Mapper</u> | <u>RADARSAT-1</u> <u>ScanSAR Wide</u> |
|----------------------------|---------------------|--|
| Frequency/Polarization | C - VV | C - HH |
| Altitude-km | 819 | 800 |
| Swath Width-km / Sub-Beams | 2 x 500 / 5 | 520 / 4 |
| Resolution-m / Looks | | |
| Science | 150 x 150 / 60 | 100 x 100 / 8 |
| Operations | 50 x 50 / 4 | |
| Antenna Dimension-m | 16.5 x 0.5 | 15 x 1.5 |
| Incidence Angle-deg | 21 - 48 | 20-49 |
| Data Rate-Mb/s | 56-102 | 105 |
| Bandwidth -MHz | 20 | 11, 17 |
| Noise Equiv. Sigma 0 -dB | < -18 (boresight) | -20 |
| Azimuth Ambiguity -dB | < -16 | -22 |
| Range Ambiguity -dB | < -18 | -18 |
| Peak Transmit Power -kW | 3.6 | 5.5 |

Summary

We have identified feasible system and orbital designs for a SAR ocean mapper that are more optimized to the spatial and temporal dynamics of ocean processes and air-sea interactions than any past, present or known future spaceborne SAR mission. The single-antenna SAR design with an 800-km swath is feasible in a 3-day repeat at 1368 km altitude, which provides near-complete coverage at the equator while maintaining favorable ocean viewing angles. A second satellite in a duplicate orbit offset by one day would further improve the repeat interval down to 1- and 2-days. Another single-antenna option is in a geosynchronous orbit, where two spacecraft could provide daily coverage of the North American coastal areas. While providing an intriguing alternative, the geosynchronous option is severely limited in terms of global coverage. The two-antenna design works favorably with two 500-km swaths in a 5-day exact repeat with 2- and 3-day sub-cycles at 819 km. While this configuration is attractive, a second satellite offset by 1-orbit would improve the sampling frequency down to 12-24 hours.

With rapidly advancing technology directed towards flying lightweight SAR antennas and electronics and hence spacecraft as means to reduce mission costs, such a dedicated mission will

become more and more economically feasible within the next several years. Perhaps most practically, these requirements and system approach can be merged satisfactorily with another dedicated mission, say for land mapping. To improve the science justification, regional climate-oriented studies are needed that incorporate SAR synergistically with other ocean sensors. To improve the operational justification, successful demonstrations are needed including, for example, the incorporation of wind measurements into wind forecast models and the ability to detect and apprehend vessels fishing illegally within restricted waters.

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